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None

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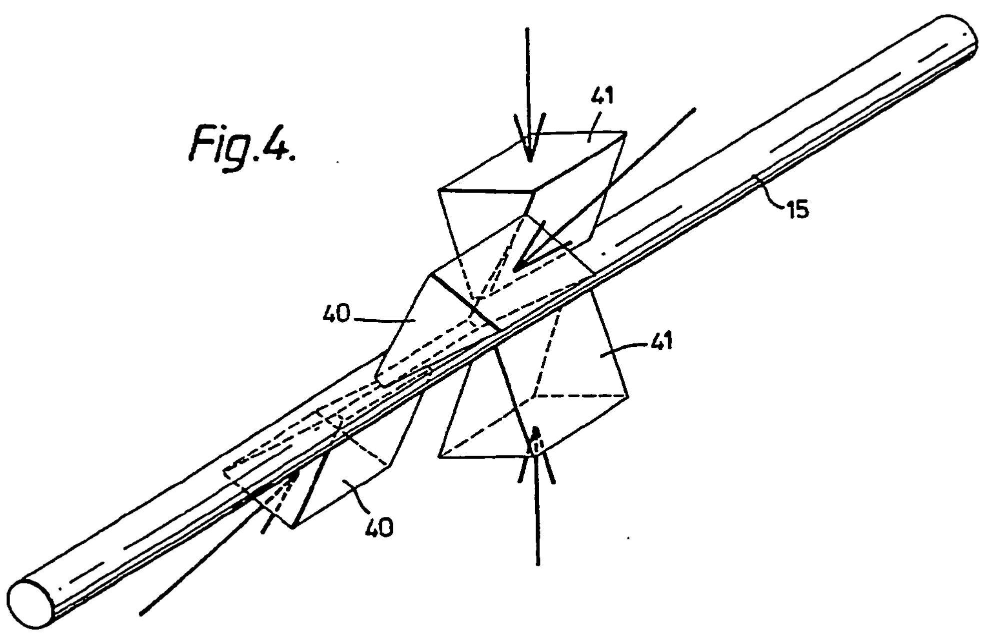
(54) Optical state-of-polarisation modulator

(57) An optical measurement system includes a polarisation modulator formed of two elements in tandem that are each cyclically driven to vary their birefringence to produce an output polarisation state that is swept over ranges such that the time integral of the system photodetector output becomes independent of polarisation. It is shown that, on the Poincaré sphere, the birefringent elements must have orthogonal eigenstate axes and be driven at different but uniform rates in order for the time-weighted distribution of output polarisation states to be symmetrical about the sphere centre.

The birefringence of the elements can thus be linear for one and circular (Faraday effect) for the other; or as shown can be linear for both if there is a relative physical orientation of 45°, as between squeezer elements 40,41 applying stress to fibre 15. The drive waveforms are each triangular with amplitudes providing full-wave changes in birefringence. The system is a reflectometer using heterodyning of backscattered light (Fig. 1).

Fig.4.



The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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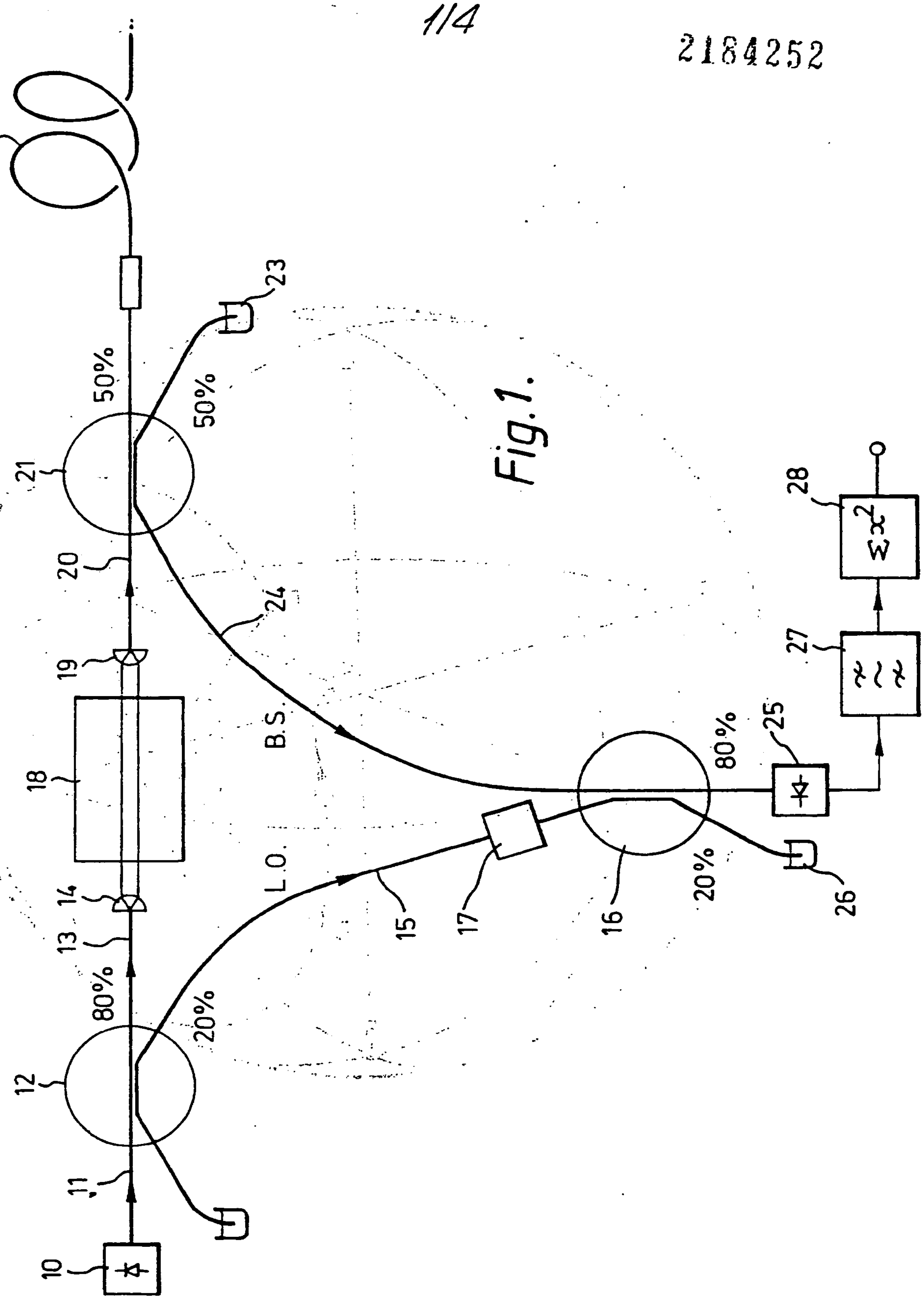


Fig.1.

Fig.2.

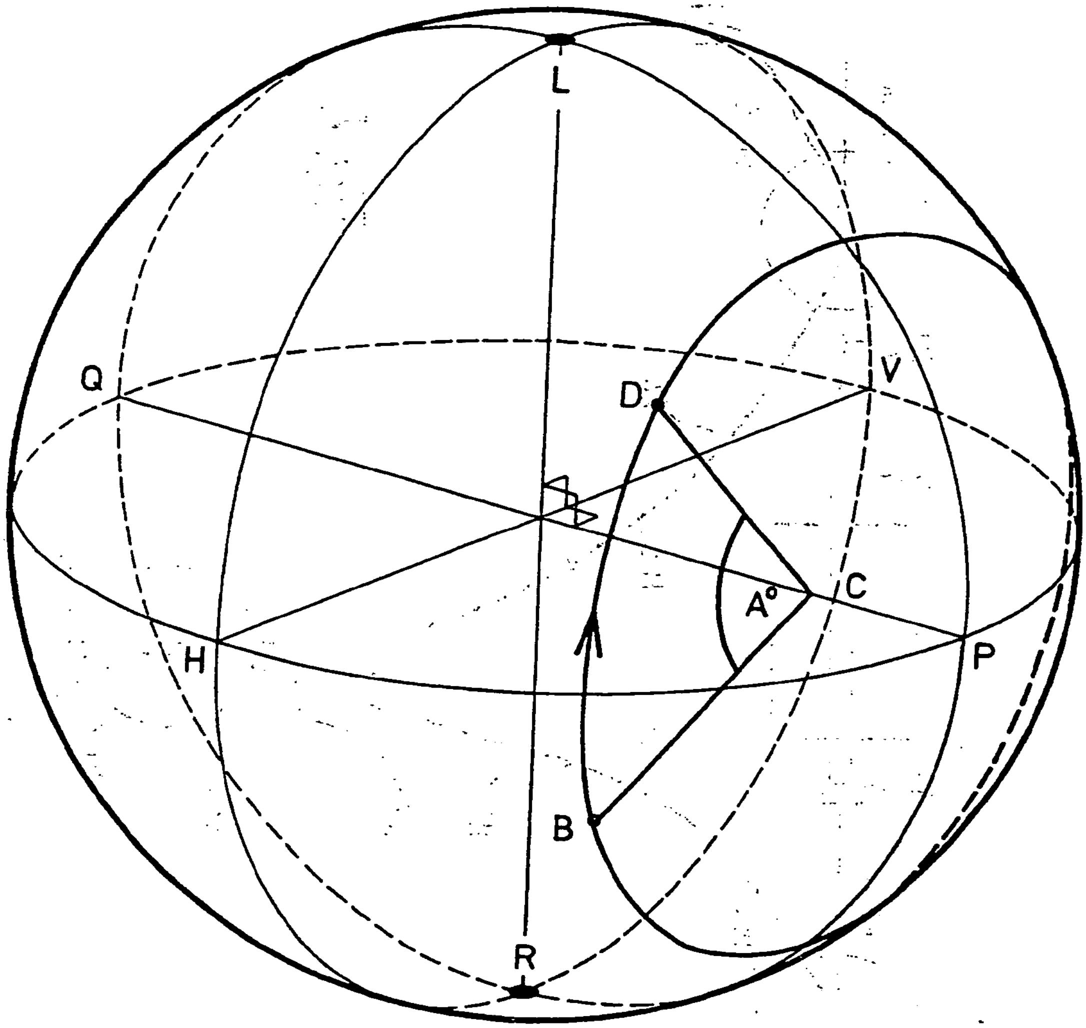
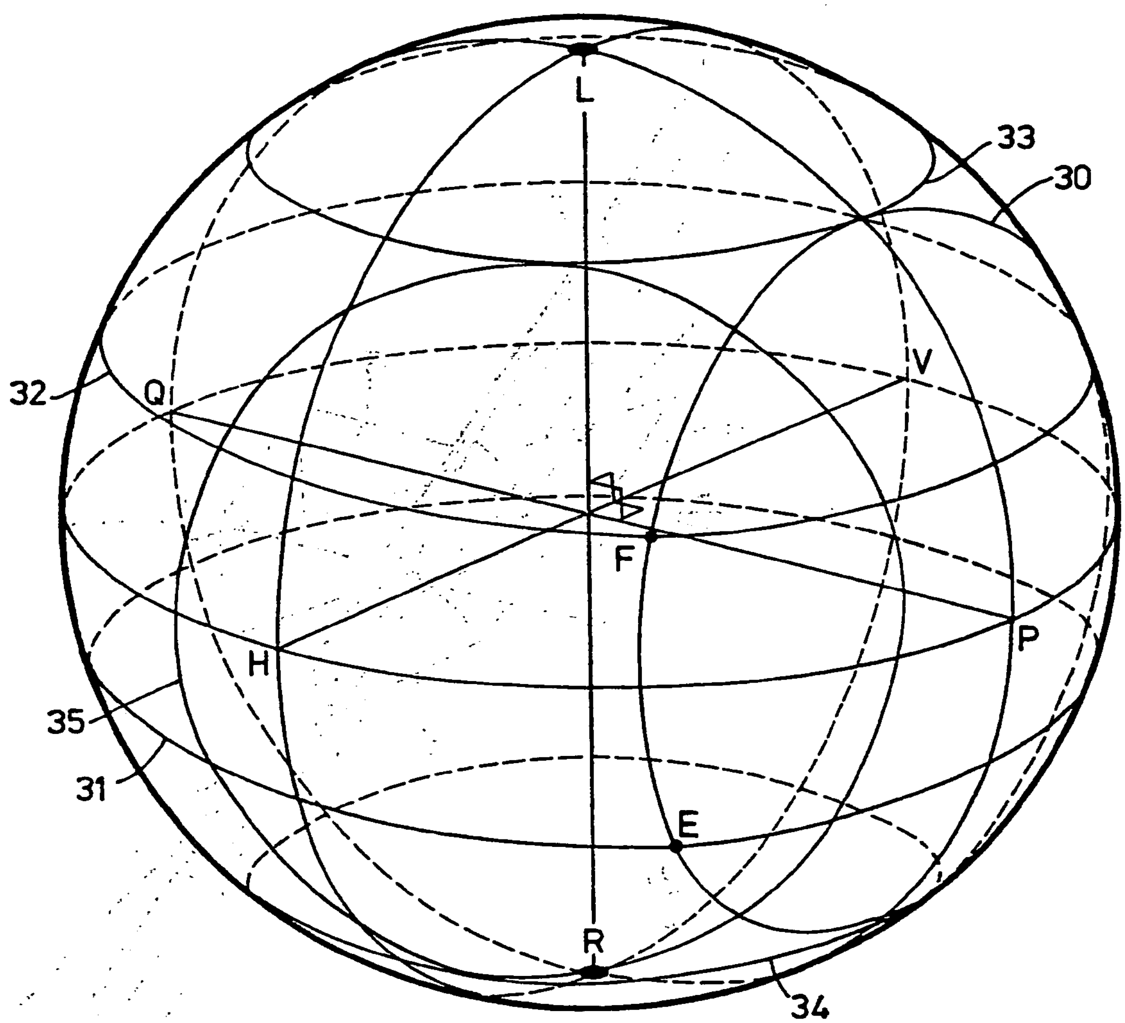


Fig. 3.



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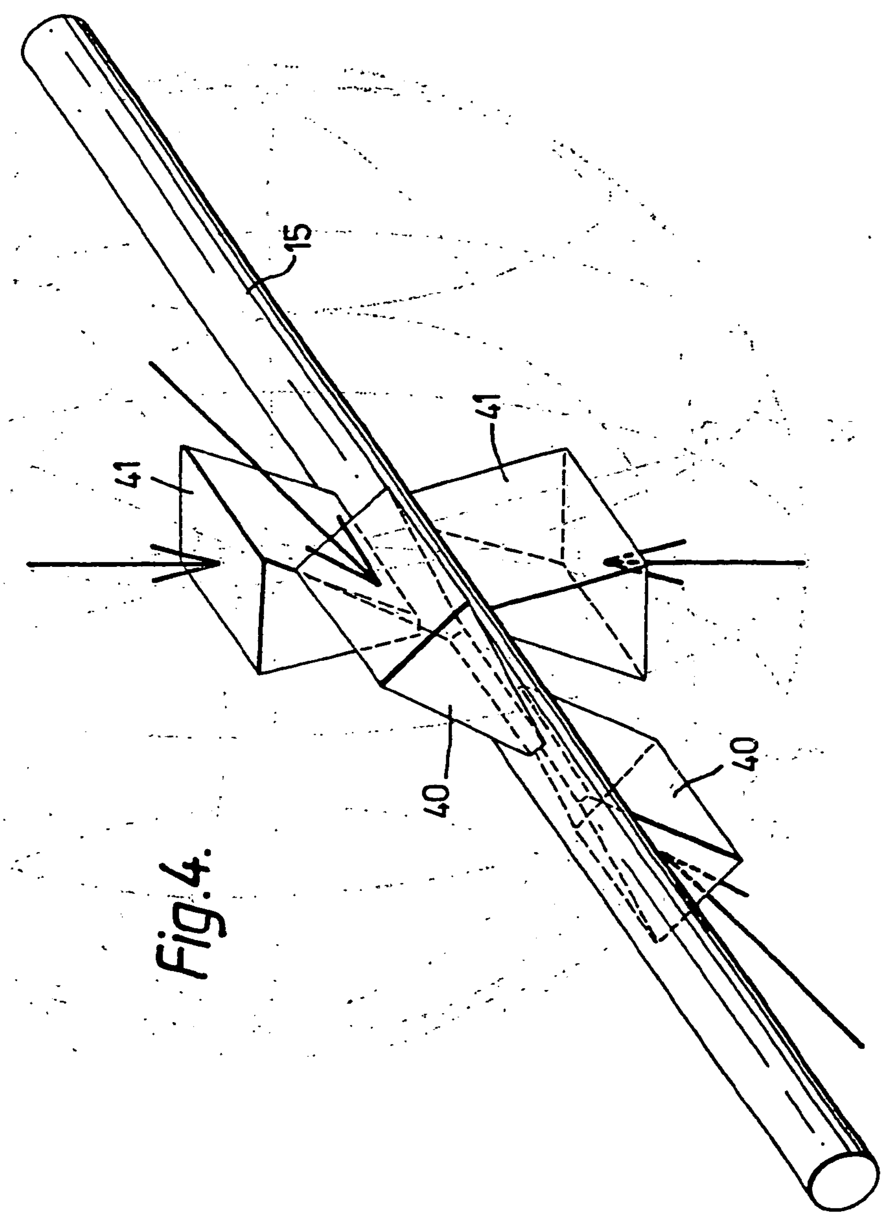

Fig.4.

SPECIFICATION

Optical state of polarisation modulation

This invention relates to optical signal processing in which light is passed through an optical state of polarisation (SOP) modulator that is operated in such a way that the SOP of its output describes a path on the Poincaré sphere that exhibits time-weighted symmetry about its centre. Such signal processing finds application in certain polarisation sensitive systems for the derivation of a detected output signal that is independent of SOP.

For example, in an optical heterodyne or homodyne system coherent light from two paths is mixed, and the amplitude of the resulting signal depends in part upon the relative SOP's of the two interfering light beams. This dependence can be inconvenient, particularly if the SOP of one of the interfering beams is unknown. A particular example is to be found for instance in a coherent light optical fibre reflectometer. In such a reflectometer the backscatter signal from the fibre under test is mixed with a local oscillator signal. The SOP of the light from the local oscillator can relatively easily be set to predetermined state, typically a linearly polarised state of a preferred orientation. However the backscattered light is generally of quite indeterminate SOP. For optimum sensitivity of the reflectometer it would be necessary to ensure that at the mixing point the two signals have the same SOP, but if the SOP of the backscattered light is indeterminate there is no obvious way of arranging to modify the SOP of the local oscillator output to match it. The optical signal processing of the present invention does not attempt to achieve this match, but it enables the local oscillator output SOP to be manipulated in such a way that the mixed signal, when arranged to fall upon a detector, will provide an electrical output signal which is readily convertible to a signal whose time-averaged value is independent of the mismatch of polarisation states at the optical mixing point.

According to the present invention there is provided an optical state of polarisation (SOP) modulator which modulator includes two variable birefringence elements optically in tandem which are arranged such that on a Poincaré sphere the birefringence (eigen state) axis of one is at right angles to that of the other, and wherein associated with each element is drive means for driving that element cyclically at a different frequency from that with which the other is driven.

The invention also resides in a method of optical signal processing in which light is transmitted through an optical state of polarisation (SOP) modulator which modulator includes two variable birefringence elements optically in tandem that are arranged such that on a Poincaré sphere the birefringence (eigen state) axis of one is at right angles to that of the other, wherein elements are driven, one at a different frequency from that of the other, so as to provide for any input SOP an output SOP that evolves on the surface of that sphere in a manner providing time-weighted symmetry at its centre.

There follows a description of a coherent light optical fibre reflectometer which incorporates an optical SOP modulator for operation in a manner embodying the invention in a preferred form. The description refers to the accompanying drawings in which:-

Figure 1 is a schematic representation of the reflectometer, and

Figure 2 is a Poincare sphere diagram illustrating the mode of operation of a single variable linear birefringence elements;

Figure 3 is a Poincare sphere diagram illustrating the mode of operation of the modulator of Figure 2; and

Figure 4 is a schematic representation of the SOP modulator of the reflectometer of Figure 1.

Referring to Figure 1, the light source for a coherent light reflectometer is provided by a laser diode 10. Light from this laser, which may incorporate a length of fibre (not shown) for line narrowing purposes, is fed by a single mode fibre 11 to a fibre directional coupler 12. The construction of the coupler is such as to transmit the majority, typically 80%, of the laser light to a further single mode fibre 13 terminating in an expanded beam collimating lens 14, while the remainder is transmitted via a single mode fibre 15 to a fibre directional coupler 16. In the optical path between coupler 12 and 16 are located an optical SOP adjustor 17. (The nature of this last-mentioned optical element will be described later). Light emerging from the collimating lens passes through a Bragg acousto-optic optical frequency modulator 18 before being collected by a further collimating lens 19 and launched into a single mode fibre 20. Single mode fibre 20 terminates in a 3 dB fibre directional coupler 21 one output part of which is connected to the fibre under test 22, while the other is connected to a total absorber 23. The 3dB coupler 21 directs half the backscattered light returning from the test fibre 22 into a length of single mode fibre 24 connecting the 3dB coupler 21 with the fibre directional coupler 16. Directional coupler 16 is constructed so that the majority, typically 80%, of the backscattered light in fibre 24 is directed to its output port that terminates in a photodetector 25. The other output port terminates in a total absorber 26. Directional coupler 16 thus acts as an optical heterodyne mixer that mixes backscattered light propagating in fibre 24 with 'local oscillator' light propagating in fibre 15 from the output of the SOP modulator 17b. The photodetector output current is fed via a filter 27 turned to the modulating frequency of the Bragg cell 18, typically 40 MHz, to an arithmetical processing unit 28, which integrates the square of the output current.

The output current of the photodetector 25 is proportional to the scalar product $\overline{E_{LO}} . \overline{E_{BS}}$, where $\overline{E_{LO}}$ is the optical field of the optical field of the light propagating in fibre 15 (local oscillator), and E_{BS} is the optical field of the light propagating in fibre 24 (backscatter).

In the case that $\overline{E_{LO}}$ and $\overline{E_{BS}}$ are both linearly polarised, and that the angle between their planes of polarisation is 'A', it is seen that the output current I, of the photodetector 25 is given by $I_1 = k.|E_{LO}|.|E_{BS}. \cos A$. Now if the

plane of polarisation of either one of these fields (but not both) is rotated by 90°, a new value of photodetector output current I_2 will result which is given by $I_2 = k.|E_{LO}|.|E_{BS}.\sin A$. It follows therefore that by squaring and summing the output currents I_1 and I_2 there is formed an output signal which is independent of the angle 'A'.

All possible states of polarisation can be uniquely represented by points on a Poincaré sphere, and on the Poincaré sphere this rotation by 90° of the plane of polarisation is represented by a rotation of 180° around the equatorial great circle (HPVQ = Figure 3) of linearly polarised states. These two linearly polarised states 180° apart on the Poincaré sphere sum to the centre of the sphere.

So far it has been shown that if one of the two interferring beams is switched between two linearly polarised states that sum to the centre of the Poincaré sphere, then by summing the squares of the resulting photodetector currents it is possible to derive a signal that is independent of the relative SOP's of the two interferring beams. It will be evident that this is also true if the switched SOP beam is not linearly polarised in either of its two states that sum to the centre of the Poincaré sphere, and it can be shown that the relationship still holds for the more general case of switching between a set of more than two SOP states that satisfy the condition that the numbers of the set sum to the centre of the sphere. Generalising further from this, it is seen that if a modulator is operated to sweep the SOP of one of the interfering beams along a path on the Poincaré sphere that exhibits time-weighted symmetry about its centre, for instance a path that sweeps at uniform rate cyclically around a great circle of that sphere, then it is possible by integrating the square of the photodetector output to derive a signal that is independent of the relative SOP's of the two interfering beams.

Referring to Figure 2, linear birefringence is represented on the Poincaré sphere as a rotation about a particular (eigen state) axis lying in the plane of the equatorial great circle HPVQ of linearly polarised states. (On this sphere the points H and V represent horizontally and vertically polarised states, the points L and R represent left-handed and right-handed circularly polarised states, and the points P and Q represent the two linearly polarised states with polarisation planes inclined at 45° to the horizontal and vertical planes. For the purpose of this specification quarter wave linear birefringence is defined to mean the birefringence afforded by an element in which the optical path length difference for its two principal directions differs by $n\lambda/4$ where λ is the wavelength of the light and n is an odd integer. Similarly half-wave linear birefringence is defined to mean the birefringence afforded by an element for which this difference is $n\lambda/2$.) Arbitrarily assigning the birefringence (eigen state) axis as the axis PQ, if the strength of the birefringence is given by a rotation of A°, then, if light enters the birefringent element with an SOP defined by some arbitrary point B, it will leave the element with the SOP defined by the point D, where the points B and D subtend an angle A_o at the centre of the (small) circle that passes through B and has its centre C lying on the birefringence axis PQ. If the birefringence is stress induced, and is increased from zero up through the value of A° to 360°, then the output SOP will first evolve along the small circle from B to D, and then all the way round the small circle back to B again. Uniform procession around this small circle will produce time-weighted symmetry about its centre C, but, if the point B does not lie on the great circle through HLVR, in no way is it possible to vary the rate of procession so as to produce time-weighted symmetry about the centre of the sphere.

One solution to this problem is to provide some form of SOP adjustor immediately upstream of the stress-induced birefringence element. This adjustor is first set to bring the SOP and the input to the stress-induced birefringence element to some point on the great circle through HLVR, and then the stress-induced birefringence element, which may for instance be constituted by a length of optical fibre laterally stressed to a PZT squeezer, can be acted upon to vary cyclically the stress applied with an amplitude providing a full-wave difference in birefringence between the points of maximum and minimum applied stress. The application of the stress has to be in a manner to provide the required time-weighted symmetry, and could conveniently be achieved by the application of a triangular waveform to the PZT squeezer to provide uniform exploration.

An alternative solution to this problem is provided by the method of the present invention. A particular feature of this solution is that it avoids the requirement for an SOP adjustor to preceded the SOP modulator. This solution involves arranging for there to be two cyclically driven variable birefringent elements driven with different frequencies and configured so that the eigen state axis of one is at right angles to that of the other. It is not immediately particularly evident that in the general case these conditions are sufficient to provide the required time-weighted symmetry, but it is more readily apparent in the particular case where the two drive frequencies are widely different.

Referring to Figure 3, and assuming for the sake of example that the two eigen state axes are respectively the PZ axis and the LR axis, then, if the input SOP to the first element is defined by some arbitrary point 'B', the modulation of this element will cause its output SOP to evolve around the small circle 30 on the Poincaré sphere that intersects the point E and has its centre lying on the PZ axis. If it is further assumed that this evolution is very slow compared with evolution of SOP produced by the modulation of the second element, then, during the first full wave modulation of this second element, the evolution of the input to this second element around small circle 30 is substantially zero. Hence during this period the output SOP from the second element will evolve substantially around the small circle 31 that intersects the point E and has its centre lying on the LR axis. At a later point in time by which the modulation of the first element has caused its output to evolve to the point F, one full-wave modulation of the second element will cause its output SOP to evolve substantially around the small circle 32 that intersects the point F and has its centre lying on the LR axis. It can be seen therefore that, in the course of a period corresponding to the full-wave modulation of the first element, the output SOP from the second element will have evolved in such a way as to cover substantially the whole of

that portion of the surface of the sphere that lies between the small circles 33 and 34 that are tangent to small circle 31 and have their centres lying on the LR axis. Clearly this provides the requisite time-weighted symmetry about the centre of the sphere under the condition that the modulation avoids introducing any bias causing either element to dwell longer at any one angle of evolution about its eigen state axis than any other. In other words the modulation of each element must be such that it exhibits a flat probability density function such as is conveniently provided for instance by a sawtooth, or a triangular, waveform of appropriate amplitude to induce a peak-to-peak difference in birefringence in that element equal to one or an integral number of full-waves.

Correspondingly, if the modulation applied to the first element is of a very much higher frequency than that applied to the second, it will be seen that the evolution of SOP provided by the modulation of the second element will produce a path in which there is formed a sequence of small circles generated from a precession of small circle 31 over the surface of the sphere by a rotation about the LR axis. Thus, after about a one-fifth full-wave modulation of the second element, a full-wave modulation of the first element will produce an SOP evolution at the output of the second element around the small circle 35. The nett result is that, as in the former instance, in the course of a period corresponding to the full-wave modulation of the more slowly modulated element, the output SOP from the second element will have evolved in a way covering substantially the whole of that portion of the surface of the sphere that lies between small circles 33 and 34.

If the two frequencies that are applied to the two elements are in simple ratio, then the output SOP will execute a closed loop path, analogous to a Lissajous figure, which can be shown to possess the requisite symmetry about the centre of the sphere except for the case where the two frequencies are identical.

A linearly birefringent material, such as a uniaxial crystal, has its birefringence (eigen state) axis lying in the plane containing the equatorial great circle of linearly polarised states of the Poincaré sphere, whereas a circular birefringent material has its eigen state axis aligned with the LR axis of the Poincaré sphere. Therefore, in order to provide the PQ and LR eigen state axes configuration discussed previously with particular reference to Figure 3, the modulator 17 of Figure 1 will consist of the tandem arrangement of a variable linearly birefringent element and a full-wave variable circularly birefringent one. Alternatively, the requirement for a variable circularly birefringent element can be avoided by choosing, as the requisite orthogonally related eigen state axes, the PQ and HV axes in which case both elements are constituted by variable linearly birefringent elements. Variable linear birefringence may be induced by the application of modulated amplitude stress to an optical element, and a convenient form for the modulator 17 of Figure 1 is provided by a length of single mode optical fibre 15 passing through two PZT squeezer elements 40 and 41 (Figure 4) oriented with their squeeze axis physically at 45° to each other so as to define directions inclined at 90° to each other in the equatorial plane of the Poincare sphere. The two squeezer elements are driven with saw tooth or triangular waveforms of different periodicity each having the requisite amplitude to induce a peak-to-peak full-wave change in birefringence.

If for some reason it was desired not to use two variable linear birefringence elements in the modulator 17, either the first of the second squeezer element of Figure 4 could be replaced by a variable circular birefringence element. Such an element can be constituted for instance by a Faraday effect element in which circular birefringence is induced by the presence of a magnetic field aligned with the direction of light propagation. Such a Faraday effect element can in principle be constituted by a length of single mode optical fibre with an appropriate winding, but at least in part because of the much larger Verdet constants currently obtainable in integrated optics structures, it would generally be preferred to employ an integrated optics version of the element. The variable circular birefringence element is like the linear birefringence elements in that it requires to be driven with a waveform having a flat probability density function, conveniently a sawtooth or a triangular waveform having the requisite amplitude to induce a peak-to-peak full-wave change in birefringence.

CLAIMS

1. An optical state of polarisation (SOP) modulator which modulator includes two variable birefringence elements optically in tandem are arranged such that on a Poincaré sphere the birefringence (eigen state) axis of one is at right angles to that of the other, and wherein associated with each element is driven means for driving that element cyclically at a different frequency from that with which the other is driven.

2. An SOP modulator as claimed in claim 1, wherein the drive means associated with each variable birefringence element is adapted to produce a modulation of birefringence exhibiting a sawtooth, or a triangular, waveform whose peak-to-peak amplitude induces a birefringence change equal to one or an integral number of full-waves.

3. An SOP modulator as claimed in claim 1 or 2, wherein at least one of the variable birefringence elements is a variable linear birefringence element.

4. An SOP modulator as claimed in claim 3, wherein the or each variable linear birefringence element is provided by a length of single-mode optical fibre and associated nechanical means adapted to act upon the fibre to provide cyclically varying strain to induce linear birefringence of cyclically varying amplitude.

5. An SOP modulator as claimed in claim 3 or 4, wherein both variable birefringence elements are variable linear birefringence elements.

6. An SOP modulator substantially as hereinbefore described with reference to the accompanying drawings.

7. An optical homodyne or heterodyne system in which there is included in the light path of one of the light beams that are coherently mixed by the system an SOP modulator as claimed in any preceding claim.

8. An optical fibre time domain reflectometer incorporating an optical system as claimed in claim 7.

9. A method of optical signal processing in which light is transmitted through an optical state of polarisation (SOP) modulator which modulator includes two variable birefringence elements optically in tandem that are arranged such that on a Poincaré sphere the birefringence (eigen state) axis of one is at right angles to that of the other, wherein elements are driven, one at a different frequency from that of the other, so as to provide, for any input SOP, an output SOP that evolves on the surface of that sphere in a manner providing time-weighted symmetry at its centre.

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